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APPLETON AS A RADIO SCIENTIST

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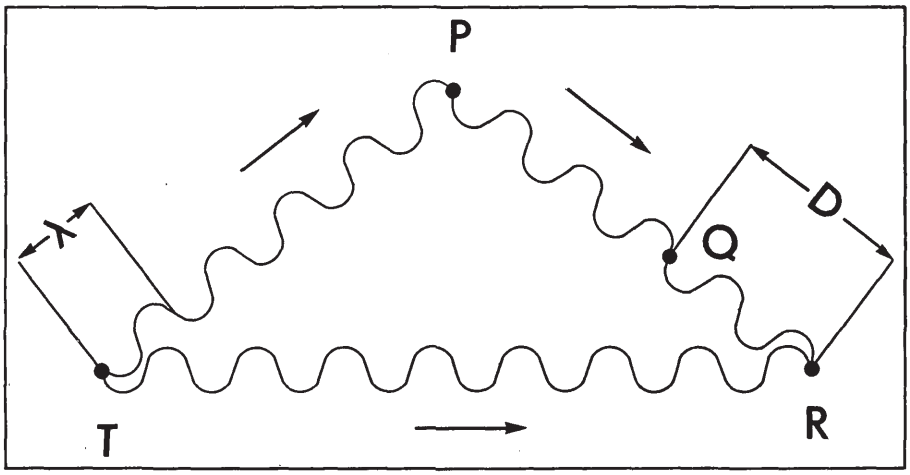
APPLETON was born in Bradford in 1892, and, after an unusually successful school career, he went to St. John's College, Cambridge, with an open scholarship in 1911. There he read for the natural sciences tripos and was awarded a first class in physics in 1914. Almost immediately the First World War started and he volunteered for service in the Army, where he ultimately found his way into the Royal Engineers as a signals officer. He there became interested in the new thermionic valve, so that when he returned to the Cavendish Laboratory in Cambridge in 1919 he started to investigate some of the ways in which it behaved as a nonlinear element in electrical circuits. These investigations were carried out in collaboration with Van der Pol, who was at the time working in the same laboratory.

Another interest of Appleton's in the years just after the war was the nature of those radio atmospherics which originate in lightning flashes and which cause unpleasant noises in radio receivers. This interest was stimulated by his friendship with C. T. R. Wilson, who was then doing some of his pioneer work at Cambridge on thunderstorms. Appleton tried to relate what Wilson was finding out about the lightning to what was known about wireless atmospherics. There followed a few papers on this subject, mainly in collaboration with Watson-Watt, who was investigating the same topics elsewhere.

Fields of research

Early in 1924 Appleton's interest was centred on these two fields of research, and to show how his mind was working we are fortunate in having available a little notebook that he kept at the time. In it there are three lists, one of papers published, one of possible papers and one of papers projected. In these lists there are 23 papers on valves or nonlinear phenomena, three on atmospherics, and, in the 'projected' list, three on radio-wave propagation.



1 Paths of waves travelling from a transmitter T to a receiver R: the path of the reflected wave TPR is greater than the path of the ground wave TR by an amount D; constructive interference occurs when $D = n\lambda$; destructive interference (fading) occurs when $D = (n + \frac{1}{2})\lambda$

Wave propagation

In April 1924, Miles Barnett arrived in Cambridge from New Zealand, intending to work with Appleton on wireless-wave propagation. It was fortunate that, just a little earlier, in 1922, the London BBC station, known to us in those days as 2LO, had started to transmit, and Barnett set to work to record the strength of the signals received from it at Cambridge. He found that during the day the signal was almost constant, but when night came on it began to vary in strength. The night-time variation was called fading, and it was supposed to be caused by a wave that had been reflected from the Heaviside layer in the high atmosphere.

This idea, that wireless waves were reflected from the upper atmosphere, was not new: in 1902, Heaviside and Kennelly had suggested that long wireless waves were guided across the Atlantic, round the great hill of the intervening ocean, by a reflecting layer high in the atmosphere. Appleton and Barnett suggested that the same layer was responsible for the fading they observed. They supposed that by day the waves reached the receiver only along the ground, but at night the reflected wave arrived in addition, so that the two were received simultaneously. When they were in phase they added, and when they were in antiphase they subtracted. It was argued that, if the path difference D (Fig. 1) between the ground path and the reflected-wave path were a whole number of wavelengths, the waves would add; if it were a whole number plus a half, they would subtract. As D changed, the resulting signal would fade. The fact that the extent of the fading increased after sunset indicated that the reflected wave increased in strength as darkness came on.

These suggestions, that there was a Heaviside layer which could bend long waves round the Earth and could reflect broadcasting waves from London down to earth at Cambridge,

were, however, no more than suggestions. What was needed was an experiment to test whether they were sound.

Interference

Appleton's and Barnett's experiences with radio waves were similar to what is observed with light waves when a Lloyd's single-mirror interference arrangement (Fig. 2) is used, and there is interference between a direct ray and a ray reflected from a plane mirror. Over the plane of observation PP′ the path difference between the two waves changes from point to point, so that interference of the two produces fringes of brightness and darkness spaced across it. If the mirror is moved the fringes move, and at a fixed point the resulting illumination alternates between brightness and darkness as successive fringes pass by: this oscillating illumination is analogous to the fading of the radio signal.

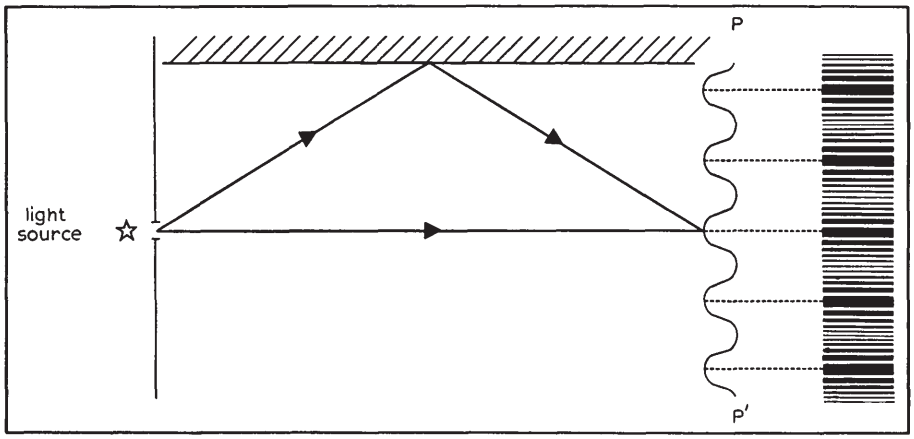
Following up this line of thought, it occurred to Appleton and Barnett that the fringes could be made to move, not only by moving the mirror, but also by altering the wavelength. If the wavelength were changed by $\Delta\lambda$ and a number of fringes represented by Δn passed a point, these two quantities would be related by the equation

$$\Delta n = (D/\lambda^2)\Delta\lambda \quad . \quad . \quad . \quad (1)$$

If a corresponding experiment could be performed for radio waves, by altering the wavelength of the transmitter, and if the corresponding fringes could be observed and counted, then from eqn. 1 the path difference D could be calculated, and from it the height of the reflecting layer could be determined. The experiment was carried out on the 11th December 1924 with the BBC sender at Bournemouth and the receiving apparatus at Oxford. Whenever the wavelength was changed, the expected fringes were observed, and, from their number, it was deduced that the reflection had been from a height of about 100km.

New technique

Almost immediately after this experiment, Appleton dropped his other research interests and concentrated all his energies on the new technique to find out more about how the waves were reflected, and about the constitution of the upper atmosphere which reflected them. Here, I think, lay his real genius. Although this was his third line of research—nonlinear phenomena and atmospherics being the first two—he realised that it held out incomparably greater possibilities for investigating those fundamental aspects of nature in which his real interest lay. He devoted the rest of his scientific life to following up the implications of what he had done, and after the list of papers in the 1923 notebook, almost all his notes and jottings related to the new work.



2 Schematic of Lloyd's single-mirror interferometer: dark fringes are produced at PP′ when direct and reflected rays interfere destructively; bright fringes are produced when the interference is constructive

Artificial fringes

He first improved the experimental technique by making the wavelength changes much more rapidly so that the artificial fringes could be clearly distinguished from the natural fading. At this stage he had left Cambridge and had become Wheatstone Professor of Physics at King's College, London. He was using a transmitter at the National Physical Laboratory at Teddington and a receiver at Peterborough. The chief interest was to investigate how the height of reflection and how the strength of the reflected wave changed over the period of dawn. Both the height and the strength decreased as the Sun's radiation built up the ionisation, and the experiment usually stopped about one hour after sunrise when the sky wave became too weak to record. An eclipse of the Sun that occurred in 1927, just after sunrise, provided an opportunity to show that the height of the Heaviside layer changed just at the time of the optical eclipse. This observation was important in suggesting that the ionisation was produced by an agency which travelled from the Sun to the Earth with the speed of light.

While these early experiments were being made, Appleton was busy thinking about how the waves were reflected and what he could deduce about the ionisation in the Heaviside layer. He modified an earlier theory of Lorentz to show how the presence of the Earth's magnetic field would affect the reflection of the radio waves through a process of double refraction. This theory, which he called the magneto-ionic theory, and particularly the equation for the refractive index, now called the Appleton–Hartree equation, has been much used in ionospheric investigations and, more recently, in investigations of laboratory plasmas. The theory was first used to show that a measurement of the polarisation of the reflected wave could be used to determine the sign and mass of the charges that caused the reflection; and it was found that these were free electrons.

In 1929 a new phenomenon began to be noticed. Sometimes the records, which were still being made on the original wavelength of 400m, contained subsidiary fringes that corresponded to waves reflected up and down twice, and naturally these were smaller than the main fringes because the twice-reflected waves were weaker; but occasionally, just before dawn, the subsidiary fringes became much larger, and the others much smaller, until sometimes only the subsidiary ones were present. It was then realised that on these occasions the subsidiary fringes represented reflections from a higher layer at about twice the height of the original one, and that they were not the result of double reflection from the first layer. Appleton called the upper layer the F layer and the lower, or Heaviside, layer the E layer. Because he himself discovered the upper one, it has sometimes been called the Appleton layer, but it is now more usual to call it the F layer, the name which he himself gave to it.

Layer nomenclature

The names E and F arose in an interesting way. In his early calculations concerning the wave reflected from the Heaviside layer, Appleton used the letter E to denote the electric field of the wave. Later, when he wished to calculate the effects of two waves, one from each layer, he denoted the second field by F. Later still, when he came to name the layers, he decided to call them by these same letters E and F so that, as he said, there were the letters A, B, C and D still left for

any layers which might later be found below E, and the rest of the alphabet for layers above F.

Once the E layer had been penetrated, attention was turned to examining the details of the penetration. First, a shorter wavelength (100m) was used, and reflections from the F layer were then observed during most of the night. It was also found that the reflected waves were stronger on the shorter wavelength, so that, for the first time, observations became possible throughout the day. Moreover, it was realised that a measurement of the critical penetration frequency, which would just penetrate the E layer, would provide a measure of the peak electron concentration in that layer, and arrangements were made to perform the wavelength-change experiment at a series of different mean wavelengths to determine which penetrated and which did not. Although the experimental procedure was slow, Appleton wrote in 1931 that it had been possible to make one determination of the critical frequency in each hour and by this method it had been shown that the peak electron concentration varied with the height of the Sun in the way foretold theoretically by Sydney Chapman.

Pulse technique

Because the wavelength-change method was too slow for determining rapid variations in the critical frequency, Appleton changed, about this time, to the pulse technique which had been used in America. In this method short trains of waves emitted by the transmitter were timed in their journey into the upper atmosphere and back, so that the height of reflection could be calculated.

In 1926 Watson-Watt had made the suggestion that the 'upper conduction layer' of the atmosphere should be called the 'ionosphere', and round about 1930 this name became widely used. By 1932 the new science of ionospheric physics was well launched, and, by making use of the pulse method over a wide range of frequencies, Appleton was rapidly accumulating data about how the ionosphere changed with the time of day, with the seasons and with the advance of the solar cycle.

In 1932 the second polar year was organised as an international effort to study all branches of science in the polar regions, and Appleton arranged for a team of workers to make ionosphere soundings at Tromsö in Norway, near the zone of maximum occurrence of aurora. There he himself recorded the first example of what is now known as a polar radio blackout, caused by particles shot into the atmosphere from the Sun.

In the Bakerian Lecture to the Royal Society in 1937, Appleton showed how, by observing the absorption of the waves, it was possible to deduce the frequency with which the electrons collided with the neutral atoms in both the E and the F regions. His measurements showed that, at the greater heights, the atmospheric density, and presumably the temperature also, were much greater than had previously been supposed.

He had always expected his measurements of the ionosphere to throw light on the 'atmospheric-dynamo' theory of geomagnetism that explained movements of the compass needle in terms of currents flowing in the high atmosphere. He knew that there were two sets of regular geomagnetic variations, one linked with solar time and one linked with lunar time; so when in 1937 he returned to Cambridge as Jacksonian Professor, he started an experiment to see whether the lunar effects could be detected if the height of the E layer were measured very accurately. By taking a long run of experimental data, and with the help of refined statistical methods of analysis, he was able to show, in collaboration with his research student Weekes, that there is a lunar tidal variation in the height of the E region, so that it is about 2km higher when the Moon is full than when it is new.

In 1938 Appleton was appointed Secretary of the Department of Scientific and Industrial Research; from then on he had no opportunity to work with research teams, and had little time to do his own work. But the remarkable thing is that, in spite of all his administrative responsibilities, both in the DSIR and later in Edinburgh University, he always remained deeply interested in anything to do with the ionosphere. He used to carry in his pocket a little notebook in which he made jottings from time to time, and, right to the end of his life, the large majority of these are concerned with problems in ionospheric physics.

Analysis of results

When Appleton moved to Edinburgh, he started, with the help of an assistant, to analyse the ionospheric results from observatories all over the world. Of course, it would not be expected that the results that he got in this way were comparable in importance with those he got earlier, but one result obtained very soon after the Second World War was certainly a major step forward. He noticed that the F layer is peculiar in that, when the Sun is overhead at the equator, a plot of the degree of ionisation shows maxima at two points, one on each side of the equator. Moreover, he found that the dip in the middle corresponds to places where the Earth's magnetic field is horizontal. Appleton saw that this so-called 'equatorial anomaly' indicated that the structure of the ionospheric F region is controlled by the Earth's magnetic field. This was a point of major importance, which is now widely accepted, and plays a prime part in ionosphere theory.

Any account of Appleton as a radio scientist would be incomplete without mention of the International Union of Scientific Radio, usually known as URSI (from the initial letters of its name in French). He early recognised that, since investigations of the ionosphere must ultimately be made in many different places, URSI would be a valuable organisation for stimulating worldwide interest. He played a leading part in it and was president from 1934 to 1952.

Laying the foundations

In conclusion, let me try to evaluate the part played by Appleton in laying the foundations of our knowledge of the ionosphere. It has to be remembered that when he started nothing was really known about it; the ionosphere was a suggestion and no more. Did it exist even? Were the charge carriers ions or electrons? How many were there? How did their number vary over the Earth with the day, the season and the solar cycle? How frequently did they collide with neutral molecules? Did the solar radiation which produced them consist of photons or of charged particles? He answered all these questions and several others, and found, quite unexpectedly, that there were two different layers with quite different behaviour, that the atmospheric density and hence the temperature in the higher one was greater than in the lower, and that the whole thing was strongly controlled by the Earth's magnetic field.

Since the Second World War, able and enthusiastic schools of ionosphere research have grown up in several different parts of the world quite independent of Appleton, and they have added very considerably to what was known of the ionosphere in 1939. Although some of Appleton's ideas have been revised, on the whole they still remain valid. But up to 1939 he was pre-eminently the leader in this work: in practically every single point of importance his was the leading paper, and I think it can be said quite fairly that what we knew about the ionosphere at that time was almost entirely due to him, or at any rate to him and to the research schools which he started and inspired.